

Field Evaluation of Digital Optical Method to Quantify the Visual Opacity of Plumes

Ke Du and Mark J. Rood

Department of Civil and Environmental Engineering, University of Illinois at Urbana-Champaign, Urbana, IL

Byung J. Kim and Michael R. Kemme

U.S. Army Engineer Research and Development Center, Construction Engineering Research Laboratory, Champaign, IL

Bill J. Franek and Kevin Mattison

Illinois Environmental Protection Agency, Des Plaines, IL

Joan Cook

Texas Commission on Environmental Quality, Austin, TX

ABSTRACT

Visual Determination of the Opacity of Emissions from Stationary Sources (Method 9) is a reference method established by U.S. Environmental Protection Agency (EPA) to quantify plume opacity. However, Method 9 relies on observations from humans, which introduces subjectivity. In addition, it is expensive to teach and certify personnel to evaluate plume opacity on a semiannual basis. In this study, field tests were completed during a "smoke school" and a 4-month monitoring program of plumes emitted from stationary sources with a Method 9 qualified observer to evaluate the use of digital photography and two computer algorithms as an alternative to Method 9. This Digital Optical Method (DOM) improves objectivity, costs less to implement than Method 9, and provides archival photographic records of the plumes. Results from "smoke school" tests indicate that DOM passed six of

eight tests when the sun was located in the 140° sector behind one of the three cameras, with the individual opacity errors of 15% or less and average opacity errors of 7.5% or less. DOM also passed seven of the eight tests when the sun was located in the 216° sector behind another camera. However, DOM passed only one of the eight tests when the sun was located in the 116° sector in front of the third camera. Certification to read plume opacity by a "smoke reader" for 6 months requires that the "smoke reader" pass one of the smoke school tests during smoke school. The average opacity errors and percentage of observations with individual opacity errors above 15% for the results obtained with DOM were lower than those obtained by the smoke school trainees with the sun was located behind the camera, whereas they were higher than the smoke school trainee results with the sun located in front of the camera. In addition, the difference between plume opacity values obtained by DOM and a Method 9 qualified observer, as measured in the field for two industrial sources, were 2.2%. These encouraging results demonstrate that DOM is able to meet Method 9 requirements under a wide variety of field conditions and, therefore, has potential to be used as an alternative to Method 9.

IMPLICATIONS

Quantification of plume opacity with digital photography has advantages when compared with EPA's Method 9 by improving objectivity, reducing teaching and certification costs, and providing archival photographic records of the visible emissions and their environments. The DOM is a digital photography-based method that was developed to quantify plume opacity using commercial off-the-shelf digital cameras. Field tests of DOM with elevated point sources demonstrate that DOM meets Method 9 requirements under a wide variety of field conditions and yields consistent results when compared with plume opacity values determined by a Method 9-qualified observer. This study indicates that digital photography is an appropriate means to quantify plume opacity and has the potential to serve as an alternative to Method 9 for determining the opacity of plumes that are emitted from elevated point sources.

INTRODUCTION

Visible plumes caused by emission of particulate matter (PM) to the atmosphere from stationary sources raise public concern about the effects of PM on human health¹ and atmospheric visibility.² The Regional Haze Rule was adopted during 1999 to protect visual air quality by reducing anthropogenic emissions to the extent that visibility is not noticeably degraded more than it would be under natural conditions.³ Standards have been developed and enforced by U.S. Environmental Protection Agency (EPA) and local authorities to regulate particulate emissions from anthropogenic sources. These emissions

Report Documentation Page				Form Approved OMB No. 0704-0188	
Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.					
1. REPORT DATE JUL 2007		2. REPORT TYPE		3. DATES COVERED 00-00-2007 to 00-00-2007	
4. TITLE AND SUBTITLE Field Evaluation of Digital Optical Method to Quantify the Visual Opacity of Plumes				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S)				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Department of Civil and Environmental Engineering, University of Illinois at Urbana-Champaign, Urbana, IL, 61801				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited					
13. SUPPLEMENTARY NOTES U.S. Government or Federal Rights.					
14. ABSTRACT					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT Same as Report (SAR)	18. NUMBER OF PAGES 10	19a. NAME OF RESPONSIBLE PERSON
a. REPORT unclassified	b. ABSTRACT unclassified	c. THIS PAGE unclassified			

can be regulated with an opacity-based standard and/or a mass-based standard. Opacity of a plume has been described as “the fraction of a light beam, which during its passage through a plume, is removed from that beam by absorption and/or scattering.”⁴ Opacity standards are established primarily because plumes can be more readily monitored by their optical rather than their mass-based properties. Both mass- and opacity-based standards should be met for stationary sources of PM. However, opacity standards established by EPA are reportedly more lenient than the corresponding mass emission standards, and, thus, a violation of opacity standard is an indicator but not proof of a violation of a mass emission standard.⁵

Methods for measuring the opacity of a plume emitted from a stationary source include the following: in-stack transmissometers, light detection and ranging (LIDAR) systems, visual observations by humans (Method 9⁶), and digital photography-based techniques. An in-stack transmissometer quantifies plume opacity within the exhaust stack of the source and requires installation and maintenance of each transmissometer at each source. An in-stack transmissometer can cost more than U.S. \$10,000. LIDAR is used as a research instrument to quantify opacity. LIDAR is even more expensive than in-stack transmissometers, is complicated to use, and is reported to underestimate plume opacity.^{7,8} Method 9 is the most common way to quantify the opacity of plumes that are emitted from stationary sources because of EPA regulatory requirements.

EPA requires “qualified observers” to pass a “smoke school” test by achieving an individual opacity error (IOE, d_i) of 15% or less and an average opacity error (AOE, \bar{d}) of 7.5% or less for all 50 black and white plumes evaluated during a particular test. IOE with unit of percent is defined as the absolute difference between an opacity value, $O_{1,i}$, that is obtained by a human or a digital camera observation and a corresponding opacity value, $O_{2,i}$, that was measured by a reference in-stack transmissometer, as described by:

$$IOE \equiv_i = |O_{1,i} - O_{2,i}| \cdot 100 \quad (1)$$

where subscript i represents each corresponding observation and measurement. AOE is defined as follows:

$$AOE \equiv \bar{d} = \frac{1}{N} \cdot \sum_{i=1}^N d_i \quad (2)$$

where N is the total number of corresponding observations and measurements for a particular test. The accuracy of a Method 9 qualified observer to determine a plume's opacity, as indicated by IOE and AOE, is influenced by the plume's background, as well as ambient lighting conditions (e.g., orientation of the sun with respect to the camera, the time of day, and the geographic location of the source⁹). Passing the test qualifies the observer to make plume opacity measurements for 6 months.

Digital photography-based methods to determine plume opacity have been under development for a few years.¹⁰ The cost can be reduced when compared with

other methods, because digital photography-based methods do not require expensive instruments, such as a transmissometer or LIDAR. Plume opacity can be determined with digital photography with a low-cost digital camera (e.g., \$300) and a personal computer to interpret the photographs (e.g., \$500). Furthermore, travel to conventional smoke schools to teach and certify “smoke readers” every 6 months is not needed. Protocols to use digital photography to determine plume opacity and to certify “digital smoke readers” can be provided through the Internet. The objectivity of the measurement to determine plume opacity is also improved, because a predesigned algorithm is used to compute the plume's opacity. Finally, permanent photographic records of the plume and its surroundings at ambient conditions are also available. These records can be useful for demonstrating compliance to regulators and providing evidence during possible legal actions.

One research group has used digital photography to quantify the opacity of plumes from stationary sources with the Digital Opacity Compliance System (DOCS).¹⁰ DOCS was developed to use a specific digital camera that self-calibrates for clear-sky backgrounds. The user can quantify a plume's opacity with DOCS software by downloading digital images that describe the plume and its background to a computer and then select an area in the photograph that includes a part of the plume where opacity is to be determined, as well as its background. The plume opacity is then calculated using the computer algorithm provided by DOCS. DOCS was tested with clear skies at a high mountain desert,¹⁰ cloudy skies with mild temperature and moderate wind,¹¹ and overcast skies with freezing temperature and light rain that was mixed with snow.¹¹ DOCS was also tested at commercial and industrial sites during rainy and misty conditions.¹² Other than being tested at smoke schools, DOCS was also tested under regulatory enforcement conditions and was compared with results from Method 9.¹³ Most recently, DOCS was tested using a range of commercially available cameras in lieu of a specific digital camera that was required to be used for the previous field campaigns.¹⁴

A new digital photography-based method, Digital Optical Method (DOM), was developed recently to quantify plume opacity.^{15–17} DOM can be used with readily-available, low-cost commercial digital cameras, with a wide range of existing backgrounds or by installing a more optimal background and with a wide range of meteorological conditions by using either a contrast model or a transmission model. DOM was initially tested under carefully controlled conditions by completing a specifically designed field campaign independent of a smoke school and under more realistic conditions by participating in a smoke school. In addition, differences in the performance of the cameras were characterized by yielding consistent results as long as they are calibrated for response curves.¹⁶ For example, the average absolute difference (AAD) is 3% between the results obtained during the previous study¹⁶ using two cameras (Canon G3 and Sony DSC S30). More thorough studies were completed later to evaluate the feasibility and flexibility of applying DOM during those more realistic conditions by comparing the opacity values obtained from DOM to opacity

values obtained from a reference in-stack transmissometer and smoke school trainees during a smoke school. Opacity measurements from DOM and from a qualified observer were also compared when monitoring industrial sources in the field. Results from these two later field campaigns are presented in this paper.

EXPERIMENTAL WORK

DOM

DOM was developed to quantify plume opacity under a wide range of ambient daytime conditions. The concepts, analytical descriptions of the models, and applications of both models were described previously¹⁶ but are briefly summarized next for clarity.

The contrast model quantifies plume opacity for clear-sky and overcast cloudy-sky conditions as long as there are contrasting backgrounds (e.g., black/white board, building/sky, etc.) behind and next to the plume. This model determines the plume's opacity from a change in contrast between each of two backgrounds that are located behind the plume and next to the plume. The contrast that is observed by the camera for the bright and dark areas of each of these backgrounds is different, because the plume changes the radiance values that originated from the background that is behind the plume but not the radiance values that originated from the background that is next to the plume. The contrast values for each of these two backgrounds are then determined by the ratio of the radiance values coming from the bright and dark areas for each of these backgrounds. The ratio of the radiances is determined by the corresponding pixel values available from the digital image by means of the camera's response curve.¹⁸ Finally, the contrast values of the backgrounds with and without the plume in front of them are then directly related to opacity with unit of percent by eq 3:

$$Opacity = \left(1 - \frac{N_{wp} - N_{bp}}{N_w - N_b}\right) \cdot 100 \quad (3)$$

where N_w and N_b are the equivalent radiance values recorded by the camera, in terms of pixel values, caused by the radiances that originate from the bright and dark areas of the background after passing through the atmosphere with no plume. N_{wp} and N_{bp} are the equivalent radiance values recorded by the camera, in terms of pixel values, caused by the radiances that originate from the bright and dark areas of the background after passing through the atmosphere that includes the plume, respectively.

The transmission model quantifies the opacities of plumes viewed in front of a uniform background that is in contrast to the plume, such as a clear sky for black or white plumes or a uniform white cloudy sky for black plumes. This model determines plume opacity based on the ratio of the radiance value from the plume to the radiance value from the plume's background, as determined by their corresponding pixel values that are recorded by the digital camera. Equation 4 is used to determine plume opacity with unit of percent by the transmission model:

$$Opacity = \left(\frac{1 - \frac{N_p}{N}}{1 - K}\right) \cdot 100 \quad (4)$$

where N_p is the equivalent radiance value recorded by the camera, in terms of pixel values, caused by radiance from the plume and path radiance of the atmosphere. N is the equivalent radiance value recorded by the camera, in terms of pixel values, from the sky and passes through the plume-free atmosphere. K is a parameter, which is determined by ambient lighting conditions and optical properties of the plumes' aerosol particles. Constant values for K of 0.16 and 1.4 are used for black and white plumes over a wide range of ambient conditions, respectively.¹⁶

DOM was developed as a Windows-based user-friendly software package. In this method, digital photographs of the plumes are taken with readily available, low-cost, commercially available digital cameras. The photographs are then processed with a specific algorithm to determine the plume's opacity as described above. The user can use either the contrast model or the transmission model based on the available field conditions. DOM was tested during sunny and overcast weather conditions with a smoke generator that was operated by Illinois Environmental Protection Agency (IEPA) personnel during 2003 and 2004. The field results demonstrated that DOM was able to consistently meet EPA requirements for IOE and AOE. Also, different cameras yielded consistent results, with an AAD in the results from the different cameras of 3%.¹⁶ The AAD between two sets of opacity observations 1 and 2 is defined as follows:

$$AAD \equiv \frac{1}{N} \cdot \sum_{i=1}^N |Opacity_{\text{observation1},i} - Opacity_{\text{observation2},i}| \quad (5)$$

In this study, three digital cameras participated in the smoke school tests, and the results obtained from the cameras were compared with those obtained by the smoke school trainees. A parameter used here to compare the frequency of occurrence for IOE values between the cameras and smoke school trainees is $f(e_i)$, which is defined as follows:

$$f(e_i) = \frac{\text{number of observations whose individual opacity error} = e_i}{\text{total number of observations}} \quad (6)$$

where $e_i = 0\%, 5\%, 10\%, 15\%, \dots$. Therefore, the percentage of observations with IOE >15% is determined by $\sum_{e_i=20\%}^{100\%} f(e_i) \cdot 100$.

Field Studies

DOM was evaluated as described here by completing two field campaigns. The first field campaign occurred during a smoke school. This campaign tested the performance of DOM based on orientation of the sun to the plume and the camera (sun angle) and the accuracy of DOM when compared with the accuracy of smoke school trainees

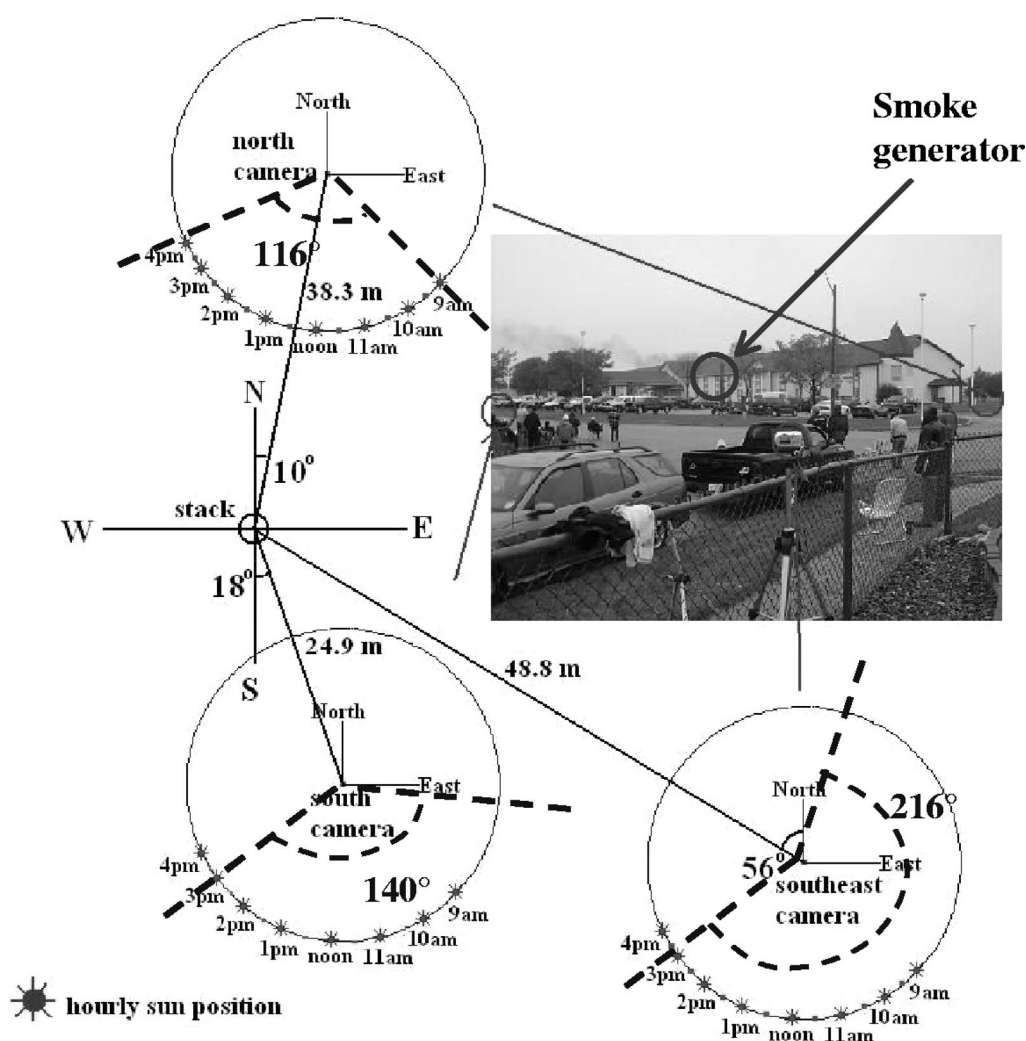


Figure 1. Site photograph and experimental layout for smoke school test. The angles 116° , 140° , and 216° describe the sectors where the sun was in front, behind, and behind the specified cameras, respectively.

during the same smoke school tests. The second field campaign evaluated DOM's ability to quantify plume opacity at two industrial stationary point sources. A qualified observer estimated the plumes' opacities using Method 9 while also determining the plumes' opacities using DOM. Opacity measurements from the qualified observer and DOM were then compared to evaluate the consistency between the two methods when used in the field.

Smoke School Field Campaign at Springfield, IL. Method 9 requires that the sun should be located within a 140° sector behind the observer. This requirement is necessary because the visual appearance of the plume depends on sun angle. The extent to which sun angle influences the ability of DOM to measure plume opacity was also tested. The smoke school occurred at an urban parking lot for a hotel in Springfield, which is a continental location that is 182 m above sea level and located at $39^\circ 48'$ north latitude and $89^\circ 39'$ west longitude. Three digital commercial cameras took pictures of the plumes from three different angles (Figure 1). Two SONY CYBERSHOT P100 cameras were located to the north and

southeast of the stack, and one MINOLTA DIMAGE Z2 camera was located to the south of the stack. The cameras were deployed at appropriate locations so that the roof and the sky, together, served as the contrasting background (Figure 1) for DOM's contrast model, which was then used to determine the plume opacities during this field campaign. The sun was within a 140° sector to the back of the south camera, 216° sector to the back of the southeast camera, and 116° sector to the front of the north camera during the smoke school tests. The three cameras were calibrated to obtain their camera response curves when those cameras were purchased. The constants for the response curves were then readily included in the DOM software to interpret the photographs from each of the cameras. The calibration procedure is simple and straightforward and can be completed within 1 hr without using additional instrument.¹⁸

The smoke generator was operated by IEPA to produce black plumes by burning toluene and white plumes by vaporizing and recondensing diesel fuel. The opacity of the plumes is adjusted by controlling the feed rates of the liquid toluene or diesel and air. The smoke generator included a stack where opacity levels were measured with

Table 1. Hourly weather conditions during the smoke school test in Springfield.

Time	Temperature (°C)	Relative Humidity (%)	Pressure (hPa)	Visibility (km)	Wind Speed (km/hr)	Sky Condition	Sun Angle	
							Altitude (°)	Azimuth (°)
October 19, 2004								
8:54 a.m.	7.8	96	1010	2.0	14.8	Mist	26.4	132.2
9:54 a.m.	8.9	93	1011	2.4	13.0	Mist	33.9	147.0
10:54 a.m.	8.9	96	1011	2.4	14.8	Mist	38.6	164.3
11:54 a.m.	9.4	93	1012	4.0	13.0	Mist	39.8	183.4
12:54 p.m.	10.0	93	1011	3.2	16.7	Mist	37.3	202.0
1:54 p.m.	10.0	96	1012	4.0	13.0	Mist	31.5	218.5
2:54 p.m.	10.6	92	1012	2.8	9.3	Mist	23.2	232.3
October 20, 2004								
8:54 a.m.	10.6	92	1018	3.2	9.3	Mist	26.1	132.5
9:54 a.m.	11.0	94	1018	4.0	9.3	Mist	33.6	147.2
10:54 a.m.	11.7	89	1018	4.8	13.0	Mist	38.3	164.5
11:54 a.m.	12.2	86	1018	9.7	13.0	Mist	39.5	183.4
12:54 p.m.	12.8	83	1018	11.3	14.8	Overcast	36.9	201.9
1:54 p.m.	13.3	80	1018	11.3	11.1	Overcast	31.1	218.3
2:54 p.m.	12.8	86	1017	9.7	13.0	Mist	22.9	232.0

an in-stack transmissometer that was calibrated by IEPA. The stack was 30 cm in diameter, and its outlet was 4.5 m above the ground.

The smoke school consisted of eight tests during 2 days with each test consisting of 25 black plumes with random levels of opacity and then 25 white plumes with random levels of opacity. The weather was misty with overcast skies, high relative humidities (80–92% relative humidities), and modest temperatures (8–13 °C). The hourly meteorological conditions and sun angle during the smoke school tests are summarized in Table 1. The meteorological data in Table 1 were obtained from the Weather Underground¹⁹ to provide an overview of the meteorological conditions during the field campaigns, which appeared to be consistent with observations. The meteorological data were not used to complete any of the data analyses. The sun angles in Table 1 were calculated according to the day of the year, time of the day, and latitude/longitude where the observations were made using the Solar Position Calculator provided by the National Oceanic and Atmospheric Administration.²⁰ The routines of Solar Position Calculator are based on the algorithm in the book authored by Meeus.²¹ Opacity values ranged from 0% to 85% for each of the black and white plumes. Each camera took two photographs for each plume, and the opacity values from those two digital images were arithmetically averaged to provide an individual DOM-generated plume opacity value. The tests started at 9:00 a.m. Central Standard Time (CST) on October 19, 2004, and ended at 3:00 p.m. CST on October 20, 2004, and resulted in 2400 digital photographs.

There were 190 people participating in the smoke school, of which 183 people eventually became certified as qualified observers. People who did not initially pass the exam could participate in subsequent exams until they hopefully passed a test before the end of the 2-day smoke school. Exams that were completed by the smoke school trainees were obtained from IEPA, and those

results were compared with the results from DOM. There were a total of 597 completed exams that were used as part of this analysis, which provided a total of 29,850 opacity measurements by smoke school trainees.

Field Monitoring of Plume Opacity by DOM and a Method 9 Qualified Observer. DOM was also implemented in the field to monitor the opacity of plumes emitted from stationary industrial sources. Opacity measurements were completed at Ft. Hood, TX, by using Method 9 and DOM. Both of these measurements were completed simultaneously by a qualified observer. Opacity results from DOM were compared with the corresponding opacity measurements provided by the qualified observer. Plumes were generated by a stack for three diesel-fired 1320-kW Caterpillar generators (facility no. 1001) and a stack for a diesel-fired 100-kW Cummins generator (facility no. 91012). Backgrounds for the plumes were either a clear sky or a building (Figure 2).

During each measurement, the qualified observer made 24 observations within 6 min with the sun located to the back of the observer, and the results of the 24 observations were averaged to provide the final average opacity value for that plume. At the same time, 24 photographs were taken for that plume and were analyzed using DOM software to determine the plume's opacity. Results from DOM for the 24 photographs were averaged to provide the final average opacity value for that plume. Eleven days were selected between September and December 2004 to make the opacity measurements. On each day, plume opacity was quantified at only one of the two sites. The observation time and meteorological conditions were recorded by the qualified observer and are summarized in Table 2. Results from simultaneous opacity measurements that were obtained from DOM and the qualified observer were compared by determining the AAD between these two measurements as described by eq 5.

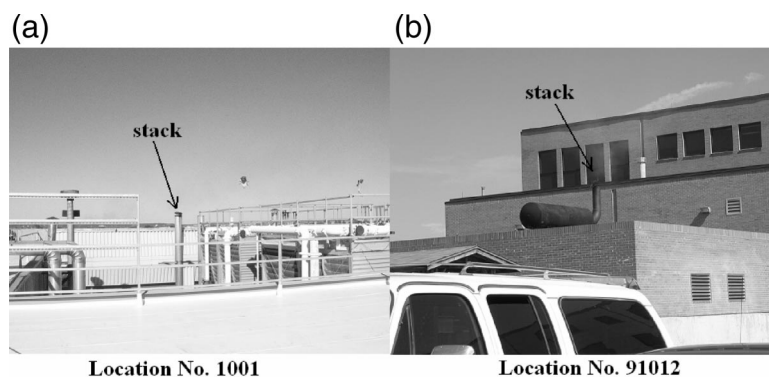


Figure 2. Photographs of the two sources at Ft. Hood: (a) Location No. 1001 and (b) Location No. 91012.

RESULTS AND DISCUSSION

Smoke School Field Campaign at Springfield

Eight tests were completed during the smoke school field campaign. For each plume, the opacity measurement from the in-stack transmissometer was deemed as the “reference” value for plume opacity. Differences between the opacity values from the transmissometer and DOM or the smoke school trainees are described by IOE and AOE values, as described by eqs 1 and 2, respectively.

Representative IOE values for 50 plumes that were obtained by the three digital cameras during the fifth test are provided in Figure 3. The bold dashed lines represent EPA’s allowable limit of 15% for IOE values. The triangles, solid dots, and open rhombi describe the results obtained with the south camera (DOM [S]), the southeast camera (DOM [SE]), and the north camera (DOM [N]), respectively. Opacity results from DOM that were obtained with the south and southeast cameras agree well with the results obtained with the transmissometer. All of the IOE values were 15% or less for all of the plumes measured by the south and southeast cameras. It is noteworthy that 86% and 80% of the IOE values for the south and southeast cameras were 7.5% or less, respectively. Good linearity was observed with all of the squares of correlation coefficients (R^2) >0.93 for all of the linear regressions between the south and southeast cameras’ results to the transmissometer’s results. As expected, the north camera did not perform as well as the south and southeast cameras. The IOE values for the north camera were 15% or less

for 90% of the 50 plumes, with 70% of the IOE values 7.5% or less. The linear regressions between the results for the north camera and the transmissometer resulted in R^2 values above 0.91.

The AOE values obtained with the three cameras during the same field test (i.e., the fifth test) that are described in Figure 3 are provided in Figure 4. All of the AOE values obtained with the south and the southeast cameras were below 7.5% for both black and white plumes. The north camera satisfied EPA’s AOE requirement when monitoring the white plumes. However, the AOE obtained by the north camera was 10.2%, which exceeds the 7.5% limit for the black plumes.

Figures 3 and 4 demonstrate that both the south and southeast cameras satisfied EPA’s IOE and AOE requirements, though the southeast camera had been placed with the sun outside of the 140° sector to the back of the camera for a portion of the tests. However, the north camera failed the test, because the sun was located in front of the camera. The reason could have been the strong radiance from the sky background, which may have saturated the camera’s pixels and resulted in large errors. Of the eight tests completed during the 2-day smoke school field campaign, the south camera passed six tests, the southeast camera passed seven tests, and the north camera passed only one test. Certification to read plume opacity by a smoke reader for 6 months requires that the smoke reader pass one of the smoke school tests during smoke school.

Table 2. Weather conditions during field monitoring while using Method 9 and DOM to quantify plume opacity at Ft. Hood.

Observation Date	Facility No.	Observation Time	Temperature (°C)	Relative Humidity (%)	Wind Speed (km/hr)	Sky Condition
9/8/2004	1001	5:14 p.m.	33.9	42	6–10	Clear
10/4/2004	91012	12:39 p.m.	25.0	70	5–10	Mostly cloudy
10/6/2004	1001	5:27 p.m.	27.8	65	11–13	Partly cloudy
10/13/2004	91012	12:08 p.m.	29.4	43	8	Mostly clear
10/19/2004	91012	12:16 p.m.	30.0	63	8–10	Clear
10/20/2004	1001	5:11 p.m.	31.7	59	11–13	Clear
10/25/2004	91012	12:31 p.m.	26.1	71	10–14	Cloudy
11/9/2004	91012	12:49 p.m.	21.1	59	10–11	Mostly clear
11/22/2004	91012	12:39 p.m.	16.7	95	10	Overcast
11/29/2004	91012	12:28 p.m.	19.4	85	5–6	Overcast
12/14/2004	91012	12:36 p.m.	10.0	21	10–11	Partly cloudy

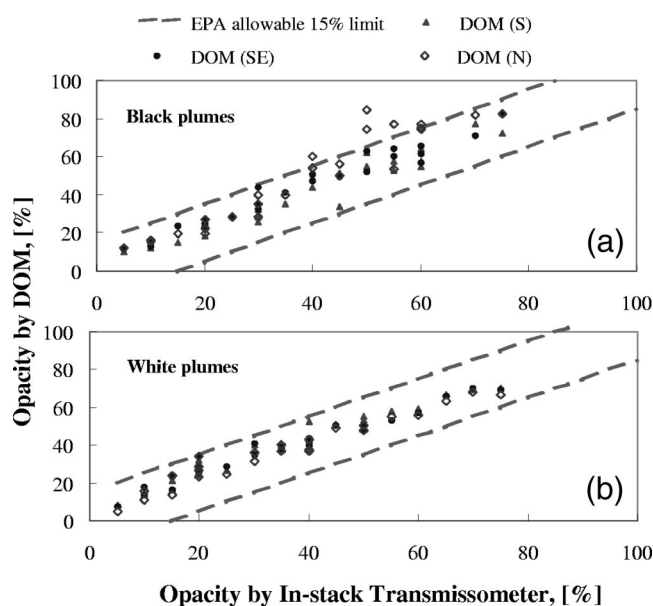


Figure 3. Typical results of IOEs for three cameras when determining plume opacity for (a) black and (b) white plumes for the fifth test.

There were a total of 400 plumes that were measured for their opacities by smoke school trainees and DOM during the eight smoke school tests. There were 0.3%, 0%, and 15.8% of the observations by DOM with IOE values above 15% for the south, southeast, and north cameras, respectively. Such results are in contrast to 4.2% of the opacity values obtained from the smoke school trainees that had IOE values above 15%. The south and southeast cameras have higher frequency of occurrences for lower IOE values (e.g., 5%) and lower frequency of occurrences for higher IOE values (e.g., $\geq 15\%$) than smoke school trainees (Figure 5). In contrast, the north camera has the lowest frequency of occurrence for lower IOE values and highest frequency of occurrence for higher IOE values. Clearly, the camera with the sun located within a 116° sector in front of the camera had the poorest IOE scores.

The mean AOE values for the eight tests with the two cameras located with the sun behind them and for the smoke school trainees were all 7.5% or less (Figure 6). Once again, the camera with the sun located in front of the camera had the highest mean AOE value above 7.5%.

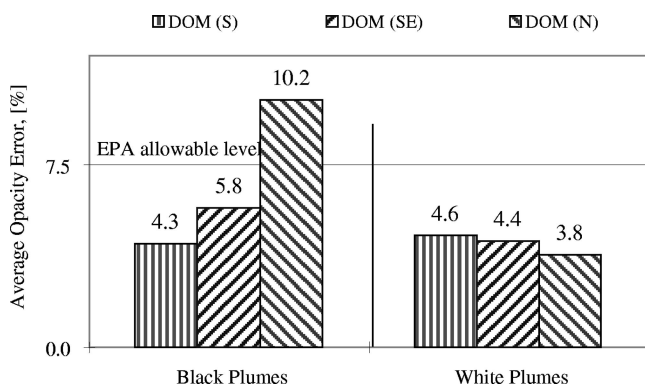


Figure 4. Typical results of AOE for three cameras when determining plume opacity for black and white plumes for the fifth test.

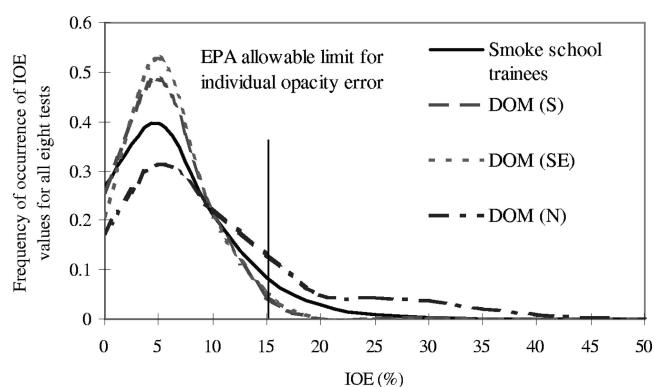


Figure 5. Frequency distributions of IOE values for smoke school trainees and the three cameras for all eight of the tests.

The t tests, at a confidence level of 99% (i.e., level of significance = $1 - 0.99 = 0.01$), were performed to analyze the results obtained by the smoke school trainees and the three digital cameras to determine whether their mean AOE values were significantly more than or 7.5% or less. Paired t tests were also performed to compare the mean AOE values of the results among the three digital cameras and the smoke school trainees. Results from the paired t test analysis confirmed the following ranking for mean AOE values, which are statistically significant with a confidence level of 99%:

south camera < southeast camera < smoke school trainees < 7.5% < north camera.

Results shown in Figures 3–6 demonstrate that the sun angle is important when applying DOM in the field. Locating the sun in front of the camera could seriously deteriorate the performance of DOM in the field. However, the specific orientation of the sun to the camera does not substantially affect DOM's ability to pass the Method 9 smoke school test if the sun is within a 216° sector behind the camera. Therefore, DOM has a broader range of appropriate locations for the camera with respect to the sun when compared with the traditional 140° sector required by Method 9. In addition, opacity values obtained from DOM are more accurate when compared with opacity values obtained from the transmissometer than the

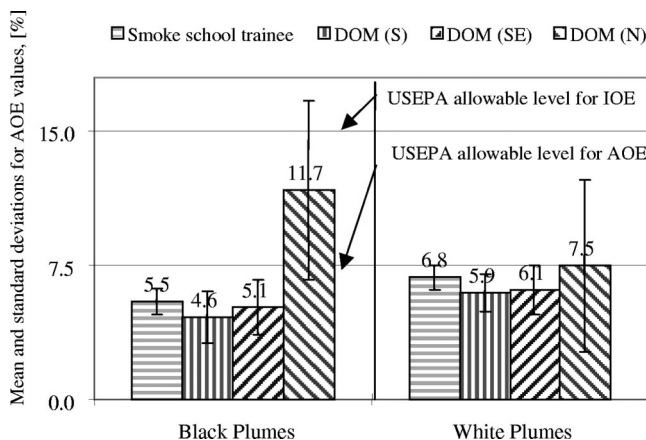


Figure 6. Means (vertical bars) and standard deviations (vertical lines) for AOE achieved by smoke school trainees and the three cameras for all eight of the tests.

Table 3. Comparison of results from a qualified observer and DOM during 11 tests at two sources while at Ft. Hood.

Facility No.	Model Used	Plume Opacity by DOM (%)	Plume Opacity by Qualified Observer (%)	Absolute Difference between DOM and Qualified Observer (%)
1001	Transmission	7.5	9.6	2.1
91012	Contrast	20.2	22.0	1.8
1001	Transmission	7.3	9.6	2.3
91012	Contrast	12.1	15.2	3.1
91012	Contrast	17.1	16.8	0.3
1001	Transmission	3.1	6.0	3.0
91012	Contrast	15.8	18.1	2.3
91012	Contrast	14.8	13.3	1.5
91012	Contrast	16.9	15.0	1.9
91012	Contrast	15.4	15.8	0.5
91012	Contrast	23.6	17.9	5.7
	Average			2.2
	Standard Deviation			1.4

corresponding opacity values obtained from smoke school trainees if the cameras are oriented with the sun located within a 216° sector behind the camera.

Field Monitoring of Plume Opacity by DOM and Method 9 Qualified Observer

Plume opacities were measured simultaneously with a qualified observer and DOM at Ft. Hood over a wide range of meteorological conditions, which included clear skies and overcast skies, RH values between 21% and 95%, and temperatures between 10 °C and 34 °C (Table 2). The backgrounds used by DOM included both the sky (for the transmission model) and a building (for the contrast model; Figure 2). Both black and white plumes were observed during the field monitoring. The AAD value for opacity values measured by DOM and the qualified observer is 2.2%. A paired *t* test, at a confidence level of 99% (i.e., level of significance = $1 - 0.99 = 0.01$), demonstrates that the results obtained by DOM are not significantly different from those by Method 9. This suggests that DOM has the capability to yield results that are consistent with Method 9 (Table 3) when used in the field with the appropriate conditions as specified by Method 9.

CONCLUSIONS

The DOM was tested at a smoke school that was operated by IPEA and located at a midlatitude continental site. The field test occurred to evaluate DOM's ability to quantify plume opacity based on viewing geometry among the camera, the plume, and the sun. DOM's ability to quantify plume opacity was also evaluated by comparing its results with the results obtained by smoke school trainees during the same Method 9 smoke school tests. All of the measured opacity values from DOM for the eight smoke school tests had AOE's less than the maximum allowable values established by EPA for cameras with the sun located in the 140° sector (south camera) and 216° sector (southeast camera) behind the cameras. Both the mean AOE's values and the percent of observations with IOE's above 15% obtained from the south and southeast cameras were lower than the results obtained by the smoke school trainees. However, the north camera, with the sun in the 116° sector in front of the sun, performed least

favorably when compared with the other two cameras and the smoke school trainees. DOM yielded the largest mean AOE value and largest percent of observations with IOE <15% when the sun was located in front of the camera. Therefore, DOM is not applicable when the sun is in front of the camera. This conclusion coincides with Method 9's requirement for sun angle with the observer looking at the plume with the sun oriented in the 140° sector to the back of the observer.

DOM was also implemented at two stationary industrial sites in Ft. Hood to compare plume opacity results with those obtained with a qualified observer. The AAD between DOM and Method 9 was 2.2%, which indicates that results from DOM are consistent with results from the qualified observer.

DOM has a number of advantages over Method 9, such as improved objectivity, low cost, and permanent photographic documentation. It is easy to implement the method, and the algorithms are available in a Windows-based user-friendly software package. In addition, DOM is able to meet EPA Method 9 requirements under the range of environmental conditions specified by Tables 1 and 2 with the sun located within a 216° sector behind the camera. These results indicate that DOM has potential to be used as an alternative to Method 9.

ACKNOWLEDGMENTS

This project was funded by the Construction Engineering Research Laboratory, U.S. Army Engineering Research and Development Center. The authors thank assistant professors David Ramirez of University of Texas A&M Kingsville and Sandeep Agnihotri of University of Tennessee for their assistance during the field campaigns.

REFERENCES

1. Xia, T.; Kovochich, M.; Nel, A.E. Impairment of Mitochondrial Function by Particulate Matter (PM) and their Toxic Components: Implications for PM-Induced Cardiovascular and Lung Disease; *Front Biosci.* **2007**, *12*, 1238-1246.
2. Boylan, J.W.; Odman, M.T.; Wilkinson, J.G.; Russell, A.G. Integrated Assessment Modeling of Atmospheric Pollutants in the Southern Appalachian Mountains: Part II—Fine Particulate Matter and Visibility; *J. Air & Waste Manage. Assoc.* **2006**, *56*, 12-22.
3. Watson, J.G. Visibility: Science and Regulation; *J. Air & Waste Manage. Assoc.* **2002**, *52*, 628-712.

4. Lilienfeld, P.; Woker, G.; Stern, R.; McVay, L. Passive Remote Smoke Plume Opacity Sensing: a Technique; *Appl. Opt.* **1981**, *20*, 800-806.
5. Conner, W.D.; McElhoe, H.B. Comparison of Opacity Measurements by Trained Observer and In-Stack Transmissometer; *J. Air Pollut. Control Assoc.* **1982**, *32*, 943-946.
6. Method 9—Visual Determination of the Opacity of Emissions from Stationary Sources. *Fed. Regist.* **1971**, *36*, 13624-13628.
7. Cook, C.S.; Bethke, G.W.; Conner, W.D. Remote Measurement of Smoke Plume Transmittance Using Lidar; *Appl. Opt.* **1972**, *11*, 209-215.
8. Alternative Method—Determination of the Opacity of Emissions from Stationary Sources Remotely by LIDAR. CFR, Part 60, Title 40, 1992; pp 855-873.
9. Alexander Weir, J.; Jones, D.G.; Papay, L.T.; Calvert, S.; Yung, S.C. Factors Influencing Plume Opacity; *Environ. Sci. Technol.* **1976**, *10*, 539-544.
10. McFarland, M.J.; Terry, S.H.; Stone, D.A.; Rasmussen, S.L.; Calidonna, M.J. Evaluation of the Digital Opacity Compliance System in High Mountain Desert Environments; *J. Air & Waste Manage. Assoc.* **2003**, *53*, 724-730.
11. McFarland, M.J.; Terry, S.H.; Calidonna, M.J.; Stone, D.A.; Kerch, P.E.; Rasmussen, S.L. Measuring Visual Opacity Using Digital Imaging Technology; *J. Air & Waste Manage. Assoc.* **2004**, *54*, 296-306.
12. McFarland, M.J.; Stone, D.A.; Rasmussen, S.L.; Calidonna, M.J.; Kerch, P.E.; Gunter, J.A. Evaluation of Digital Opacity Compliance System at Military and Commercial Industrial Sites; *Fed. Facilities Environ. J.* **2004**, *15*, 73-81.
13. McFarland, M.J.; Rasmussen, S.L.; Stone, D.A.; Palmer, G.R.; Wander, J.D. Validation of the Digital Opacity Compliance System under Regulatory Enforcement Conditions; *J. Air & Waste Manage. Assoc.* **2006**, *56*, 1260-1266.
14. McFarland, M.J.; Rasmussen, S.L.; Stone, D.A.; Wander, J.D.; Spencer, M.T.; Gunter, J.D. Field Validation of Visible Opacity Photographic Systems. In *Proceedings of A&WMA's 99th Annual Conference & Exhibition*, A&WMA: Pittsburgh, PA, 2006; Paper 304.
15. Du, K.; Rood, M.J.; Kim, B.J.; Franek, B.; Mattison, K. Evaluation of Digital Image Method to Quantify Opacity of Stationary Source Plumes. In *Proceedings of A&WMA's 97th Annual Meeting & Exhibition*, A&WMA: Pittsburgh, PA, 2004; Paper 64.
16. Du, K.; Rood, M.J.; Kim, B.J.; Kemme, M.R.; Franek, B.; Mattison, K. Quantification of Plume Opacity by Digital Photography; *Environ. Sci. Technol.* **2007**, *41*, 928-935.
17. Du, K.; Rood, M.J.; Kim, B.J.; Franek, B.; Mattison, K. Field Testing of the Digital Opacity Method to Quantify Plume Opacity. In *Proceedings of A&WMA's 98th Annual Conference & Exhibition*, A&WMA: Pittsburgh, PA, 2005; Paper 1278.
18. Kim, B.J.; Kemme, M.R.; Du, K.; Rood, M.J. *Scientific and Technical Basis for the Innovative Digital Optical Method (DOM) to Measure Plume Opacity Using Digital Camera Images*; Draft Technical Report; U.S. Army Engineer Research and Development Center—Construction Engineering Research Laboratory (ERDC-CERL): Champaign, IL, in press.
19. *Weather Underground*; available at <http://www.wunderground.com/history/> (accessed 2005).
20. *Sun Position Calculator*; available at <http://www.srrb.noaa.gov/highlights/sunrise/azel.html> (accessed 2005).
21. Meeus, J. *Astronomical Algorithms*; Willmann-Bell, Inc.: Richmond, VA, 1991.

About the Authors

Ke Du is a Ph.D. candidate and Mark J. Rood is the Ivan Racheff Professor of Environmental Engineering within the Department of Civil and Environmental Engineering at University of Illinois at Urbana-Champaign. Byung J. Kim and Michael R. Kemme are environmental engineers within the U.S. Army Engineer Research and Development Center, Construction Engineering Research Laboratory. Bill J. Franek and Kevin Mattison are environmental scientists within the Illinois Environmental Protection Agency. Joan Cook is an environmental engineer within Texas Commission on Environmental Quality at Austin. Address correspondence to: Mark J. Rood, Department of Civil and Environmental Engineering, University of Illinois at Urbana-Champaign, 3213 Newmark Civil Engineering Laboratory, 205 N. Mathews Ave, Urbana, IL 61801; phone: +1-217-333-6963; fax: +1-217-333-6968; e-mail: mrood@uiuc.edu.

Copyright of *Journal of the Air & Waste Management Association* (1995) is the property of Air & Waste Management Association and its content may not be copied or emailed to multiple sites or posted to a listserv without the copyright holder's express written permission. However, users may print, download, or email articles for individual use.